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ORIGINAL ARTICLE

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The critical rotational speed of circular saw: simple measurement method and its practical implementations

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Abstract Operation safety during sawing operations as well as dimensional accuracy and surface roughness depend on circular saw dynamic features among other factors such as circular saw blade accuracy and static/dynamic properties of the machine tool. Manufacturers of saw blades have an obligation to mark tools with a value stating the maximum allowed rotational speed for each saw. However, in some cases the value indicated on the saw corresponds to the critical rotational speed or is dangerously close to this critical value. Saw operation at the critical rotational speed is inadvisable and may result in serious injury or depreciation of product quality. This report outlines a simple methodology for evaluation of circular saw critical rotational speed. The assessment was conducted with a camera vision technique on the basis of an impulse test. Results are compared with theoretically calculated critical rotational speeds and the marks on saw blades.

Key words Circular saw · Critical rotational speed · Saw blade vibration · Vision technique

Introduction

The critical rotational speed of the circular saw determines the maximum saw rotation speed for which routine saw stability can be assured. When rotation speed reaches the critical speed range, the clamped saw blade cannot resist transverse forces and becomes unstable. The task of addressing this problem is of the great importance. Operational safety during sawing as well as dimensional accuracy and the surface roughness produced depends on the circular saw dynamic features among other factors (such as circular saw blade accuracy and static/dynamic properties of the machine tool). Manufacturers of saw blades are obliged to mark tools with a value stating the maximum allowed rotational speed for the saw. The usual way to determine maximum rotational speeds of the saw is based on the value of maximum rim speed. According to the literature, the sawing speed should not exceed 100 m/s.[1] This method is currently utilized by most of producers of circular saw blades. However, in some cases the value indicated on the saw corresponds to the critical rotational speed or is dangerously close to this critical magnitude. It was demonstrated that maximum (or permissible) rotational speeds marked by the tool producers on the saw blades are occasionally higher than the computed/experimental critical rotational speed of these saws. In the example discussed by Stakhiev,[2] the mark on the saw was 1500 rpm while the calculated speed for this saw was only 1173 rpm. It is clear that in the speed range from 1173 to 1500 rpm, the circular saw would easily become unstable and pose a hazard to the people working with it.

Critical rotational speed theory of the circular saw has been a subject of many scientific publications. The effect of monolithic saw geometry (such as diameter, clamping ratio, and blade thickness) on the saw dynamic behavior was researched by Schajer,[3] Stakhiev,[4,5] and Siklienka and Svoren.[6] The result of the saw guides was investigated by Schajer.[7] Some works were dedicated to optimization of saw tensioning.[2,5,8,9] Chabrier and Martin[10] published a review of methods for monitoring circular saw blade preparation. Li et al.[1] analyzed varied factors restricting the rotary speed of circular saws such as material strength, welding seam, vibration properties, and the blade structure construction. The effect of slots on the lateral vibration of the circular saw blade has also been studied.[9,11–13] Moreover, Münz[14] found that there is a correlation between critical speeds and residual stresses in the saw blade caused by the technological process (grinding).

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Although critical speed theory seems to be well accepted by the scientific community, the practical implementation of this theory is rather limited. Methodologies of the critical speed computations existing in the literature are too specific for straightforward application in industry. Moreover, the critical speed depends on some additional factors, such as internal stresses, tensioning, or temperature gradients. Numerical evaluation of such complex systems is even more complicated and hardly applicable out of laboratories. An alternative way for determination of critical speeds is through experimentation. This method could be easily adopted by saw blade producers and final tool users. The goal of the present study was to develop a simple experimental methodology for evaluation of circular saw critical rotational speed.

Calculation of circular saw critical speed from natural frequencies

According to the critical rotational speed theory, each saw blade vibration is a superposition of two traveling waves (the forward traveling wave and the backward traveling wave) moving in opposite directions around the saw blade. This was well demonstrated by Stakhiev.[2,5] Figure 1a illustrates an effect of the rotation speed on the transverse displacement of the idling circular saw during gradual increase of the rotation speed. Stakhiev distinguished the following characteristic speeds:

- the universal rotational speed n_u,
- the optimal rotational speed n_o,
- the permissible rotational speed n_p,
- the lowest critical rotational speed n_{cr}^{min},
- the lowest self-excited rotational speed n_{aut}^{min},
- the destructive rotational speed n_{des}^{min}.

The natural frequency f_n for the nodal diameter number n of the running circular saw blade is influenced by the rotational speed N of the saw blade and it may be written as a function $f_n(N)$. Therefore, the frequencies of the forward and backward traveling waves may be written as follows:[3,5,11,15]

forward traveling wave:

$$f_{nf}(N) = f_n(N) + \frac{nN}{60} \tag{1}$$

backward traveling wave:

$$f_{nb}(N) = f_n(N) - \frac{nN}{60} \tag{2}$$

When the rotational speed of the circular saw increases, the frequency of the backward traveling wave becomes zero at a certain rotational speed, which is called the critical (lowest) rotational speed n_{cr}^{min}.[5,15] This is a resonance point where a small lateral force causes a large lateral deflection of the saw blade.[2,5] There is no critical rotational speed in the cases of nodal diameter $n = 0$ and $n = 1$. In most cases, the lowest critical speed is for the nodal diameter $n = 2$.[5] It must be also mentioned that the mode n when the lowest critical speed appears also depends on the ratio of collar and saw blade diameters.[3]

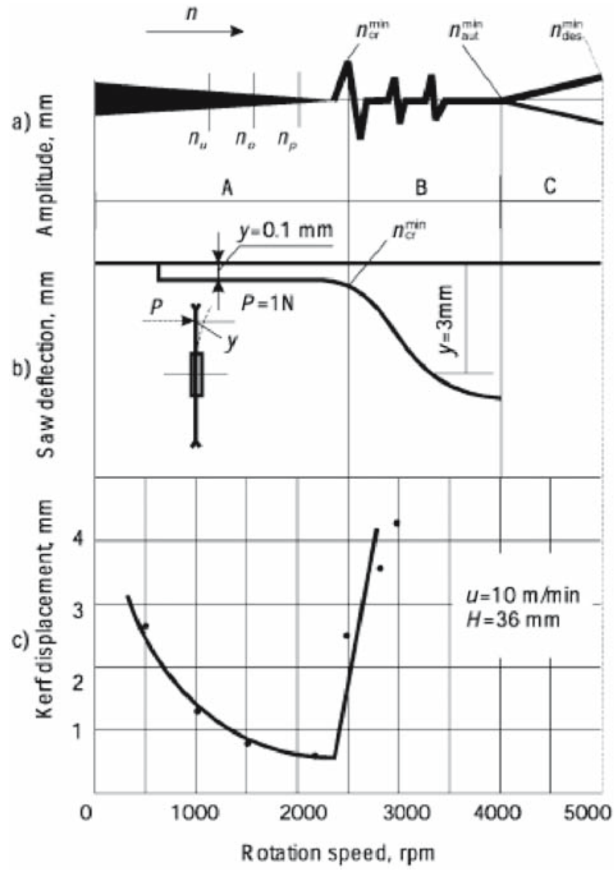


Fig. 1a–c. Circular saw blade behaviors as a function of rotational speed: **a** amplitude, **b** saw deflection, **c** kerf displacement. *A*, Idling (force $P = 0$ N); *B*, force $P = 1$ N; *C*, sawing of timber, ($H = 36$ mm, feed speed $u = 10$ m/min, saw diameter 510 mm, clamping diameter 125 mm). Reprinted from Stakhiev[9]

The lowest critical speed n_{cr}^{min} may be calculated from Eq. 3:

$$n_{cr}^{min} = \frac{60 f_n(0)}{\sqrt{n^2 - K}} \tag{3}$$

where K is the centrifugal force coefficient (a dimensionless constant independent of the rotational speed), $f_n(0)$ is the value of natural frequency of the nonrunning saw blade for the nodal diameter n.

Values of circular saw natural frequencies $f_n(0)$, for solid circular saws without slots, may be obtained, for example, with special software (e.g., CSAW developed by Schajer[16]), from Stakhiev's tabulated data (normalized in the Russian Standard[17] or from Stakhiev[5]), or from numerical models calculated with finite element methods (FEM).[11]

However, for the "real-world" circular saws (with external and internal slots, tensioned and with thermal fields), the natural frequencies may be determined experimentally, i.e., obtained from the impulse excitation test. In this method, values of $f_n(0)$ can be comprehended from fast Fourier

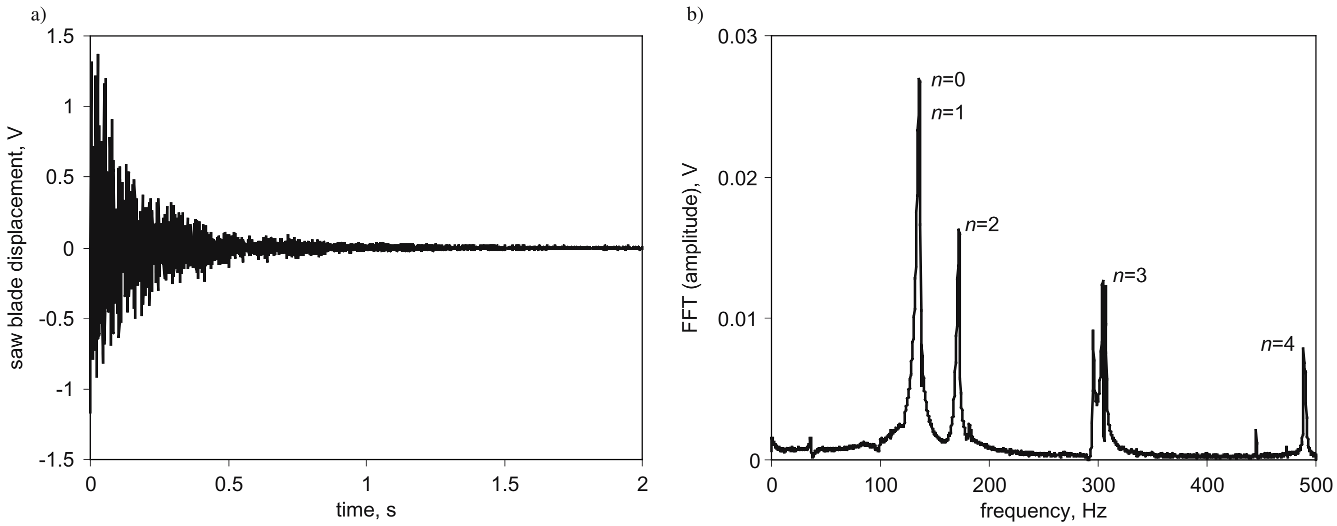


Fig. 2a,b. Determination of the natural frequencies of the circular saw: **a** time domain data from eddy current displacement sensor, **b** fast Fourier transform of the time data, (saw diameter $D = 305\,\text{mm}$, hole diameter $d = 30\,\text{mm}$, saw blade thickness $s = 3.2\,\text{mm}$, $A/D = 0.41$)

transform (FFT) of the time course of the circular saw displacement signal (Fig. 2).

Theoretical and experimental values of K for solid saw blades are given in the literature.[3,5,11] Unfortunately, there is a lack of K parameter data for some more complex circular saws (such as saws with a large number of slots).

Determination of the critical rotational speed: example of computation

For the experimental computation of the critical rotational speed, the circular saw should be fixed on the spindle of the circular sawing machine. In this example we used a saw that is commercially available on the European market. It has a diameter $D = 305\,\text{mm}$, thickness of 3.2 mm, and hole diameter $d = 30\,\text{mm}$. According to the manufacturer, the optimum rotational speed was 4300 rpm and the maximum rotational speed was 6200 rpm. These values are a result of the "traditional" assumption of the maximum rim speed of the circular saw, usually considered as $n_r = 100\,\text{m/s}$.

The saw was mounted with collars of diameter $A = 125\,\text{mm}$ (clamping coefficient $A/D = 0.41$). Then, the nonrotating saw was excited by hitting it with a small hammer. The transverse displacements were measured with an eddy-current displacement sensor mounted close to the saw surface at the radius close to the gullets.

An example of the time data acquired by the sensor and its fast Fourier transform (amplitude spectrum) are shown in Fig. 2. The clear characteristic peaks can be noticed in the frequency spectrum (Fig. 2b). Each peak corresponds to the saw blade's static natural frequency of subsequent nodal diameters ($n = 0, 1, 2 \ldots$). It must be pointed out that natural frequencies of $n = 0$ and $n = 1$ are almost equal[3–5,16] and they are roughly marked in position of the first meaningful peak in the frequency spectrum.

Computations began with calculation of the critical rotational speed of the saw using Eq. 3:

$$n_{\mathrm{cr}}^{\min}(f_{n=2}(0)) = 7398\,\text{rpm} \tag{4}$$

The above value was calculated with the natural frequency for nodal diameter $n = 2$, read from Fig. 2b, of $f_n = {}_2(0) = 172.2\,\text{Hz}$, and with constant $K = 2.05$ for a saw blade with slots.[11]

The permissible rotational speed may be calculated according to Stakhiev:[2,5,9]

$$n_p = 0.85 \cdot n_{\mathrm{cr}}^{\min} = 6289\,\text{rpm} \tag{5}$$

Due to a large value of the clamping coefficient ($A/D = 0.41$), all computations had to be repeated for mode $n = 3$:[3–5]

$$n_{\mathrm{cr}}^{\min}(f_{n=3}(0)) = 7333\,\text{rpm} \tag{6}$$

The above value was calculated with the natural frequency for nodal diameter $n = 3$, read from Fig. 2b, of $f_{n=3}(0) = 304.34\,\text{Hz}$, and with constant $K = 2.8$ for a saw blade with four slots.[11]

The corresponding permissible rotational speed may be calculated as in Eq. 5:

$$n_p = 0.85 \cdot n_{\mathrm{cr}}^{\min} = 6233\,\text{rpm} \tag{7}$$

The obtained results revealed that in the case of a large value of clamping ratio, the minimum critical rotational speed is obtained for nodal diameter $n = 3$. It is very important to note that this minimum critical rotational speed it is only slightly larger than the maximum value of the rotational speed that is marked on the saw by the manufacturer. Furthermore, it should be noted that improper tensioning or hitting of the saw may reduce the critical speed even more. Therefore, working with such a saw at the maximum rotational speed indicated by the manufacturer may result in the depreciation of the product quality, or, even worse, can be dangerous for the user of the saw. This conclusion motivated authors to develop a simple methodology for determination of critical (permissible) rotational speeds of

circular saws that can be used by wood industries and tool suppliers.

Vision system for circular saw critical speed evaluation

Utilization of the eddy current sensor for collecting data is a common procedure. It usually provides satisfactory results; however, in some cases it is difficult to mount the sensor directly on the machine in the cutting zone, very close to the saw blade. Therefore, we proposed an alternative to the eddy current technique. We applied a noncontact machine vision approach.

The setup of the hardware was a typical triangulation arrangement, and is illustrated in Fig. 3. A laser light projector (StockerYale, 10 mW, 635 nm) was directed onto the circular saw blade (mounted on the standard machine) at a small angle. The image of the area surrounding the spot was taken by the CMOS video camera (PixelLink PL-A782) equipped with a telecentric lense (Computar, TEC-M55). The images from the camera were continuously acquired by a laptop computer (P4, 3 GHz, 1 GB RAM) through a fireware (IEEE1394) interface. Depending on the optics, the camera, and the computer speed, the captured image can vary in size. In this experiment, the captured image was 288 pixels wide and 48 pixels high.

It was possible to achieve a top scanning speed of 1400 frames per second with the hardware used, but balancing the image quality (shutter time) and expected dynamics of the signal (the Nyquist criterion), the images were captured with at 700 frames per second. To determine the natural frequencies of the saw blade it was necessary to vibrate the saw by hitting the blade with a small hammer. The laser spot position seen by the video camera changed according to the saw blade deflection; therefore, it was possible to analyze the amplitude of the circular saw vibrations.

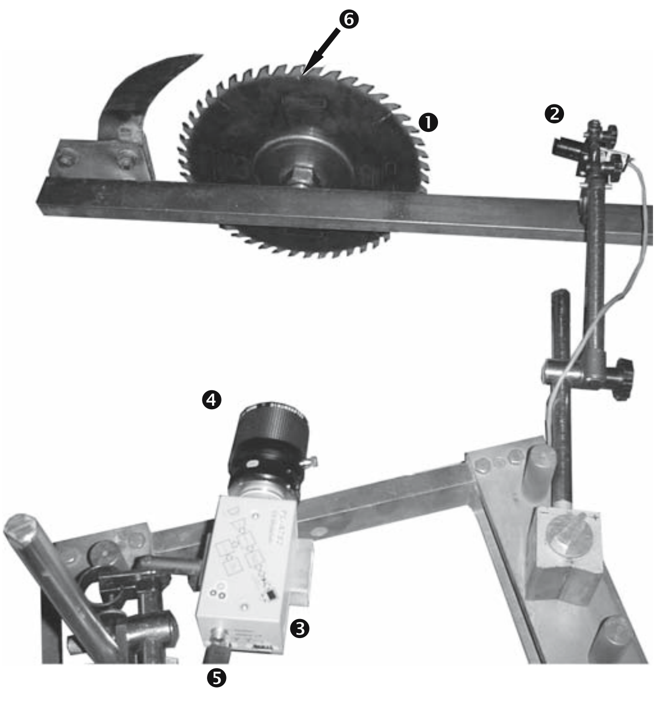


Fig. 3. Setup for in-field critical saw blade speed estimation: *1*, circular saw; *2*, laser projector; *3*, video camera; *4*, telecentric lens; *5*, fireware (IEEE1394) connection cable; *6*, laser spot on saw blade surface

The data stream was saved on the computer hard disk as an AVI file and stored for further processing. A special program was developed in LabView 7.1 for processing of the images. The software calculated the center of gravity of the spot for each captured frame. As a result, the change of the spot center position over time was recorded. The transformation of the time data into a frequency spectrum by fast Fourier transform was the last step. The resulting functions corresponded closely to the functions obtained earlier with the eddy current sensor.

This setup was applied for determination of critical rotational speeds of two, brand-new circular saw blades (Gass). Detailed data of examined saws:

- Saw 1 (CS1): outside diameter $D = 350$ mm, hole diameter $d = 30$ mm, saw blade thickness $s = 2.5$ mm, teeth number $z = 18$, collar diameter $A = 125$ mm, clamping ratio $A/D = 0.35$ (Fig. 4a);
- Saw 2 (CS2): outside diameter $D = 280$ mm, hole diameter $d = 30$ mm, saw blade thickness $s = 2.6$ mm, teeth number $z = 48$, collar diameter $A = 125$ mm, clamping ratio $A/D = 0.44$ (Fig. 4b).

Results and discussion

Due to the value of the clamping ratio *A/D,* the critical rotational speeds of the examined saws were evaluated with Eq. 3 for two nodal diameters $n = 2$ and $n = 3$. Both examined saws had four slots; thus, the constant $K = 2.05$ (for $n = 2$) and $K = 2.80$ (for $n = 3$).[11] The values of characteristic frequencies $f_{n=2}(0)$ and $f_{n=3}(0)$ were obtained from corresponding amplitude spectrums (Fig. 4). Each spectrum is the result of averaging five consecutive measurements. It should be emphasized that the occurrence of the frequency ~24 Hz in both FFT spectra is an effect of the dynamic properties of the measurement system and this frequency was disregarded in the analyses.

Calculation results of critical and permissible rotational speeds are summarized in Tables 1 and 2 for CS1 and CS2, respectively. Additional rows are appended to present the rotational speed recommended by the manufacturers [$n_r(100)$; corresponding to 100 m/s saw speed]. As verification of the vision system, supplementary rows present results obtained from CSAW v.3.1[16] and data taken from Stakhiev.[5]

Unfortunately, all additional results were calculated for saws without slots. External slotting of the solid saw blade causes decreased saw blade stiffness to a higher degree than reduction of its mass. Thus, decreased natural frequencies are also expected. This phenomenon is clearly visible in Tables 1 and 2. It should also noted that the radical decrease

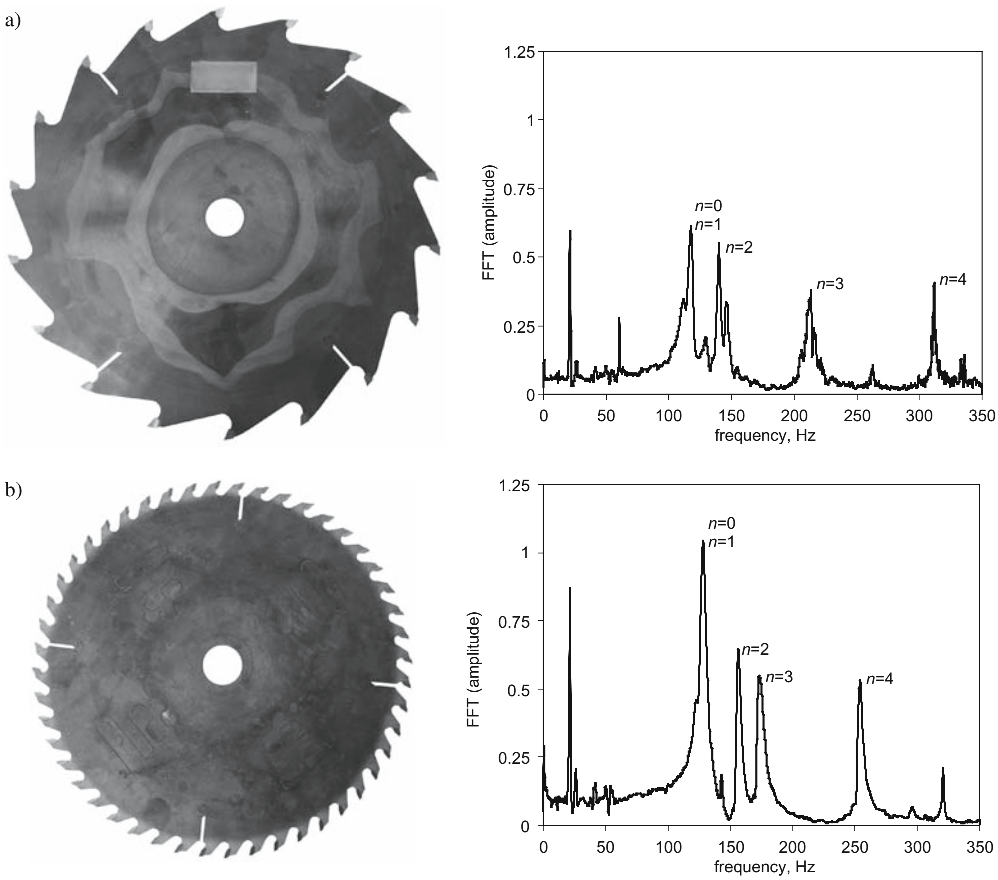


Fig. 4a,b. Effect of the saw geometry on the circular saw critical speed determined with the vision technique: **a** circular saw 1 (CS1), **b** circular saw 2 (CS2)

Table 1. Natural frequencies, critical rotational speeds, and permissible rotational speeds of the circular saw CS1 determined with different computational methods

Method	Nominal nodal circle mode number	Nominal nodal diameter mode number	Natural frequency $f_n(0)$			Centrifugal force coefficient K	Critical rotational speed n_{cr} (1/min)	Permissible rotational speed n_p (1/min)
			A/DS = 0.285 (Hz)	$c_{A/D}$	A/D = 0.357 (Hz)			
CSAW[a]	0	2	–	–	188.6	–	–	–
	0	3	–	–	287.0	–	7437	6321
Stakhiev's data[a]	0	2	161.7	1.42	229.6	2.43	10995	–
	0	3	272.9	1.09	297.4	3.58	7666	6516
Experiment $f_n(0)$	0	2	–	–	140	2.05	6015	5113
	0	3	–	–	213	2.80	5133	4363
100 m/s cutting speed	–	–	–	–	–	–	–	5450

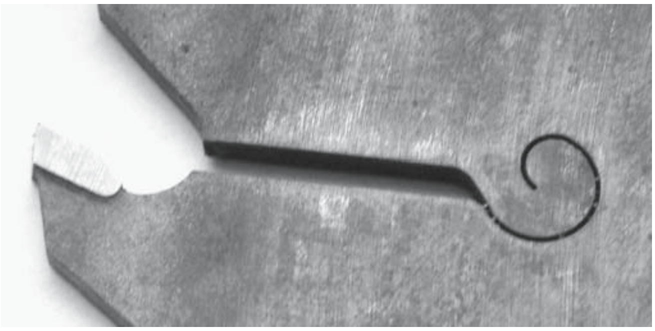
A/DS, Clamping ratio for Stakhiev's data;[5] $c_{A/D}$, correction factor of clamping ratio
[a] Calculated for number of slots SN = 0

Table 2. Natural frequencies, critical rotational speeds, and permissible rotational speeds of the circular saw CS2 determined with different computational methods

Method	Nominal nodal circle mode number	Nominal nodal diameter mode number	Natural frequency $f_n(0)$ A/D = 0.357 (Hz)	Centrifugal force coefficient K	Critical rotational speed n_{cr} (1/min)	Permissible rotational speed n_p (1/min)
CSAW[a]	0	2	402.1	–	–	–
	0	3	540.5	–	14014	11912
Experiment $f_n(0)$	0	2	157	2.05	6746	5734
	0	3	173	2.80	4168	3543
100 m/s cutting speed	–	–	–	–	–	6820

[a] Calculated for number of slots SN = 0

a)



b)

Fig. 5a,b. Detail of the CS2: **a** hooked ending of the slot, **b** internal slots

in the permissible rotational speed of circular saw CS2 is caused by both hooked endings of external slots (as shown in Fig. 5a) and four internal slots with a brand name cut through the saw blade (see Fig. 5b).

The results obtained revealed that the lowest critical and permissible rotational speeds for the saw blades under examination were for vibration mode $n = 3$. In every case, the speed values obtained experimentally were lower than the speeds recommended by the manufacturer.

Conclusions

Producers and users should reconsider their evaluation of the critical speeds of circular saws. The maximum values of rotational speeds marked on saws by manufacturers are occasionally larger than values obtained experimentally. In some cases the value indicated on the saw corresponds to the critical rotational speed or is dangerously close to this critical value. Saw use at or near the critical rotational speed is inadvisable and may result in serious injury or depreciation of product quality. These considerations become more important as pressures are imposed to increase production speed and improve product quality while still ensuring the safety of the personnel.

The presented experimental setup, based on the vision technique, may be efficiently utilized for determination of the circular saw blade critical rotational speed outside of the laboratory. Calculation of the permissible speeds of circular saws by using Stakhiev's equations seems to be the simplest and the most effective way for such evaluation. However, for cases in which saw slots are present, reduction in the value of constant K should be considered.

At present, the authors are cooperating closely with some saw blade manufacturers in Europe. It seems that they appreciate the new methodology and are applying it to the quality control of their products as well as for in-field diagnosis of wood machining problems. The methodology of saw blade marking has been also revised to mark saw blades with a realistic maximum rotational speed.

Acknowledgments This work is dedicated to the memory of Dr. Yury Mikhailovich Stakhiev (1934–2004), who was an acknowledged expert in the field of circular saws and a pioneer in the development of the critical speed theory. Part of this research has been done as a postdoctoral project financed by Provincia Autonoma di Trento. Special thanks is due to Gass, Suwalki (Poland) for providing the saws used in the experiment.

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